AC-DC Thermal Transfer Instruments

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RMS value is desired, in most cases, since rate of transformation of energy from electrical to other forms is proportional to RMS values.

Can not accurately deduce one measure of a waveform (e.g. RMS, average, peak) from another unless the exact waveform is known.

Types of Instruments which inherently rely on RMS or mean-square principles:

- Electrodynamic - force between current carrying conductors

- Electrostatic - force between charged conductors

- Electrothermic - comparison of heating effect produced by ac and dc signals in a current carrying conductor

Electronic Instruments:

- Rectified average responding

- Analog or digital squaring, integration, and square root

- Sampling

- Electrothermal

We <u>choose electrothermal</u> over electro-mechanical because:

- the instrument’s performance can be evaluated by purely electrical means
- the method offers greater measurement resolution and accuracy
- and because it is free from resonances and other mechanical effects.

The electrothermal device is strongly desirable as a <u>primary standard</u> because:

- structure is conducive to modeling
- its simple construction permits analysis of the underlying physics of the instrument’s limitations.

Thermal converters are used as transfer instruments therefore undesirable effects such as:

- very high temperature coefficient
- heater aging
- first order drift of range resistors or shunts
- transfer of heat to surrounding structure

are generally minimized or eliminated.

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Major factors producing ac-dc difference in thermal converters:

a) Thermoelectric effects which affect the temperature
rise on dc, but, due to integration, not on ac
e.g. Thomson heating effects, Peltier effects

b) Failure to thermally integrate signal at low frequency

c) Skin effect in heater or signal path

d) Reactance of heater structure

e) Reactance of range resistors or transfer shunts

f) Leakage current and bead dielectric loss

If ac-dc difference = 0
Then the transfer process implies:
dc power in heater = ac power in heater

$$\frac{V_{dc}^2}{R} = \frac{1}{\tau}\int_0^{\tau} \frac{V_{ac}^2}{R}\,dt \qquad (1)$$

and

$$RMS\ Voltage_{ac} = \sqrt{\frac{1}{\tau}\int_0^{\tau} V^2\,dt} \qquad (2)$$

so from (1) and (2)

$$V_{dc} = rms\ V_{ac}$$

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Choose thermal over electronic as standards because even if the “constants” in the defining equation vary with temperature or over time,

the relation that

$$\textit{Heater temperature} = \textit{function of } (I_{rms})^2$$

still holds!

If the constants of the internal relationships change in electronic methods, then the functional form actually changes.

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Temperature relationship for a thin homogeneous conductor, with a current i flowing in the x direction,
the temperature rise, Q, is given by:

$$\frac{\partial^2\Theta}{\partial x^2} - \frac{H\Theta}{K} + \frac{i^2 R}{K} = \frac{1}{D}\frac{\partial\Theta}{\partial t}$$

where

$\Theta = temperature\ rise$

$H = rate\ of\ surface\ heat\ loss\ per\ degree\ rise$
$for\ a\ unit\ length$

$K = Thermal\ Conductance$

$R = Electrical\ resistance$

$D = Thermal\ diffusivity$

$N.B.$

$k = thermal\ conductivity = \frac{Power}{l\Theta}$

$and\ K = \frac{kA}{l},\ A = cross\ sectional\ area$

$\frac{1}{D} = \frac{K}{MS},\ S = Specific\ heat$

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Integrating over one period

$$\frac{1}{\tau}\int_0^\tau \frac{\partial^2\Theta}{\partial x^2}\,dt - \frac{1}{\tau}\int_0^\tau \frac{H\Theta}{K}\,dt + \frac{1}{\tau}\int_0^\tau \frac{i^2 R}{K}\,dt = \frac{1}{\tau}\int_0^\tau \frac{1}{D}\frac{\partial\Theta}{\partial t}\,dt$$

Restoring terms	$\frac{H\Theta}{K}$	$\frac{R}{K} I_{rms}^2$	Thermal integration $\Rightarrow$ Small

$\therefore\ \Theta = f(I_{rms}^2)$ *If* Θ *is constant over cycle.*

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Definition:

$$AC\text{ - }DC\ Difference\ \delta = \frac{Q_a - Q_d}{Q_d}$$

Where Q_a is the AC signal

and Q_d is the average of the two polarities of dc

which produce the same output indication

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An ac-dc calibration is performed by the comparison of a test instrument to a calibrated standard.

Nominally the same voltage applied to Thermal Voltage Converters (TVCs) in parallel.

Nominally the same current through Thermal Current Converters (TCCs) in series.

(Can be thermoelement shunted by a transfer shunt)

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Single junction thermoelement (SJTE) construction:

- *Thin wire heater - commonly a nickel chromium alloy*
- *Evacuated glass envelope - normally mounted in shielded enclosure for electrical, thermal, and light shielding*
- *Feed-through leads commonly of dumet (copper-clad iron alloy) or platinum*
- *Thermocouple - commonly chromel constantan - mechanically attached to, but electrically insulated from, the heater*
- *Glass insulating bead*
- *Temperature rise of about 150 K - 200 K above ambient*

$$E = kI^n$$

where E = thermocouple output voltage
I = current through the heater
k = constant
and n is close to 2

"n" is level dependent because:

(A) heater resistance changes with temperature

(B) thermal conductivity of structure may be temperature dependent

(C) radiation heat loss is higher order than second, "n" is generally 1.6 to 2.0

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Single junction thermoelements - new design

- *evanohm heater - smaller temperature coefficient*
- *Pt-Ir leads - smaller skin effect*
- *cold-set bead - to avoid over heating of evanohm alloy*
- *thermal shunts at heater ends - to reduce thermoelectric effects*

Main causes of dc reversal error:
(Normal heating is Joule heating)

Asymmetric heating on different dc polarities
Asymmetric thermal construction

Asymmetric heating -
Thomson and Peltier effects.
Thomson effect is the production or absorption of heat as a result of an electric current flowing through a temperature gradient.

Heat is absorbed in one part of the heater and liberated in another part; this process may not accurately reverse when the current is reversed.

Thomson effect continued -

On ac, the heat liberated during one half cycle is equal to the absorbed during the next half cycle.

Even though there may be a dc reversal error, it does not produce a large ac-dc difference providing

(a) the thermocouple is at the thermal center of the heater or

(b) the output on ac is compared to the mean of the outputs for the two polarities of dc, i.e. dc reversal is employed.

Dc reversal error:

(a) varies from one thermoelement to the next

(b) is level dependent - see Inglis' data

(c) may change with time

(d) definitely does change under overload conditions.

After a momentary overload, the dc reversal of a particular TE was changed by 5000 x 10^{-6}. The change in the ac-dc difference negligible!

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Thermal voltage converter sets -Frequency range from low audio to about 100 kHz:

- *Range resistors and TEs mounted in separate coaxial, shielded enclosures*

- *Level independent resistors*

- *Overlapping ranges to permit build-up or build-down*

- *Internal compensation shields on high voltage ranges*

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Higher frequency thermal voltage converters - up to 100 MHz:

- *Low reactance, coaxial design*
- *May be modeled as cylindrical waveguide*
- *No intervening connectors*
- *Metal film or deposited carbon resistors*
- *Nearly flat frequency coefficients up to 1 MHz*

Thermal current converter (TCCs) and transfer shunts

- *NIST standards are two types of thermoelements*

  1 mA to 500 mA - vacuum type

  1 A to 20 A - Weston/NBS design, air cooled, temperature compensated

- *Most have Evanohm heaters*

- *Higher current ranges have tubular heaters*

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Primary Standards

A group of Multijunction Thermal Converters (MJTCs)

MJTCs are the result of attempts to fabricate perfect thermal converters

MJTCs are used by most, large national metrology laboratories as primary standards

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A Group of MJTCs with bifilar heaters

50 - 200 thermocouples

Different designs, different sources and times of manufacture

5 mA - 50 mA, 2 V - 10 V Inputs; 30 mV - 120 mV outputs

Average ac-dc difference of the Primary Group:

$<0.5 \times 10^{-6}$ from 30 Hz to 10 kHz

Voltage extension from the 2 V - !0 V levels of the primary MJTCs is by build-up or build-down using reference and working standards.

Level independence studied and confirmed.

Adjacent ranges are compared at the voltage of the lower of the two ranges.

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Extension of current ranges from the 5 mA - 50 mA region of the primary MJTCs other special SJTEs is by current build-up.

•Up to 1 A - two TEs are:

compared in series;

connected in parallel and then the combination compared in series with two TEs of a higher range;

alternatively they may each be connected in series with one of a pair of matched resistors to form a TVC and these TVCs then compared

•*Above 1 A two TEs are:*

compared in series at lower current

Frequency dependence of 5 mA TEs is checked up to 100 kHz using two matched resistors to form 30 V TVCs.

Frequency Extension

First method suitable for frequencies ranging up through 1 MHz:

•Converters constructed with very similar geometry and of similar materials but with > 2:1 ratio of series resistors

•TEs checked for small ac-dc differences as current converters

•Major sources of ac-dc difference expected to contribute proportionately different amounts

•Results show confirm that 10 V to 25 V ranges built with different resistors have very similar ac-dc differences up to 1 MHz

Second frequency extension method:

- *Study of transmission line characteristics of TVC structural elements in the frequency range 1 MHz to 100 MHz*

- *Transimpedance modeled and measured for region of resistor*

- *Voltage at back of input connector determined using open-circuited, air transmission line*

- *Current standing wave in region of TE modeled and tested using two TEs in series*

- *Models and method suitable down to 1 MHz, but also yields ac-dc differences up to 100 MHz*

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Basically Two Types of Comparators

Converter outputs nulled against each other

Converter outputs monitored separately

Both can be realized using modern instrumentation

Recharacterization of TVCs after thermoelement replacement:

Resistance of new TE should match within a few percent

Phase angle of candidate TE should match within 1 mrad to ensure that phase angle term can be neglected

Need change in ac-dc difference as both TVC and TCC, so
compare new TE and old TE as voltage converters - e.g. lowest voltage range
compare new TE and old TE as current converters - e.g. use similar range resistors

Apply equation to obtain new ac-dc differences

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Simple Protective Circuit

Back-to-back diodes directly in parallel with heaters

Zeners chosen to be about twice supply voltages

An expendable thermoelement in series to serve as fuse

TEs with large reversals make good, inexpensive fuses

Equal-Time-Interval Data Collection

Thermal converters have large temperature coefficients

Made for low ac-dc difference, not necessarily for best magnitude stability

After some warn-up, drift can be approximated as linear over short time internal, even if more than one time constant is present

High voltage and current have noticeable drift; expect lowest uncertainty for lower ranges; so must remove at least first order drift from all comparisons

Novel thermal converter technologies

Thin-film MJTCs

Integrated micropotentiometers

Transistor or diode sensor thermal converters (so called solid-state)

CMOS foundry MJTCs

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Transistor or diode sensor thermal converters

Small thermal mass - short thermal time constant

High level output

Under production by more than company

Used in voltage calibrators, DVMs, as well as transfer standards

Safety Considerations

For Both Operator and Equipment

Always keep outer shell of TVC at ground potential

Operate with one side of the TE output grounded - bead or other insulation will only withstand a few tens of volts

Avoid measurement of heater or bead continuity with ohmmeter having high output current - most modern ohmmeters are okay